§13. Population Inversion and Gain of X-ray Spectral Lines of Be-like Ions in Recombining Plasmas

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We have constructed a collisional-radiative model (CRM) to calculate population densities, $n(i)$, of the excited states of Be-like ions, Fe^{22+} and Ne^{6+} in recombining plasma, to calculate population densities and to examine the population inversion and laser gain coefficients. We assume quasi-steady state for solving the rate equations, including radiative transitions, collisional excitation and deexcitation, collisional ionization, radiative recombination, dielectronic recombination, and three-body recombination. In the CRM, $2snl$ levels with n up to 70 (Fe^{22+}) or 20 (Ne^{6+}), and $2pnl$ levels with n up to n_{th} (11 for Fe^{22+} and 6 for Ne^{6+}) are included.

The population inversions are found in recombining plasma at some electron density and temperature regions, for example, between 2s3s ^{3}S and 2s3p ^{3}P levels or between 2s3d ^{3}D and 2s4f ^{3}F levels. Here we focus on 3d-4f transition to examine the laser gain coefficients for NeVII and FeXXIII lines in recombining plasma, since the gain coefficient of AlX 3d-4f transition (177.8Å) in laser produced plasma has been measured by Hara *et al.*(1989) to be $3.5 \pm 0.5\text{cm}^{-1}$ [1].

Figure 1 shows the normalized population density, $n(i)/(g(i)n_e n_+)$ of 2s3d, 2p3d, 2s4f, and 2p4f levels as a function of electron density in a recombining plasma for NeVII, where n_+ is ion density of Li-like Ne and $g(i)$ is the statistical weight. The population inversion occurs at $n_e < 10^{18}\text{cm}^{-3}$ for $T_e = 7\text{eV}$.

In Fig. 2 we show the contour maps of the normalized gain coefficient, $G' = G/(n_+ R)$, of the 2s3d ^{1}D - 2s4f ^{1}F transition for NeVII and FeXXIII at the line center of the Gaussian line profile in a plane of scaled electron density and temperature, i.e. n_e/z_{eff}^7 and T_e/z_{eff}^2, where G is a gain coefficient with the usual definition and $R = \lambda/\Delta\lambda$, spectral resolving power. Roughly, $G' \propto z_{eff}^2$ is found from the plots, and then $G \propto z_{eff}^8$ if $n_+ = n_e/z_{eff}$.

If we apply this scaling law to the AlX 2s3d ^{1}D - 2s4f ^{1}F transition with plasma parameters $T_e = 6\text{eV}$ and $n_e = 10^{19}\text{cm}^{-3}$, the gain coefficients is expected to be $G \sim 4(R/500)\text{cm}^{-1}$ if $n_+ = n_e/z_{eff}$. This is consistent with the coefficient measured by Hara *et al.* if $R \sim 500$.

References
[1] Hara T, Ando K, Kusakabe N, Yashiro H, and Aoyagi Y 1989 Japanese J. Applied Phys. **28** L1010

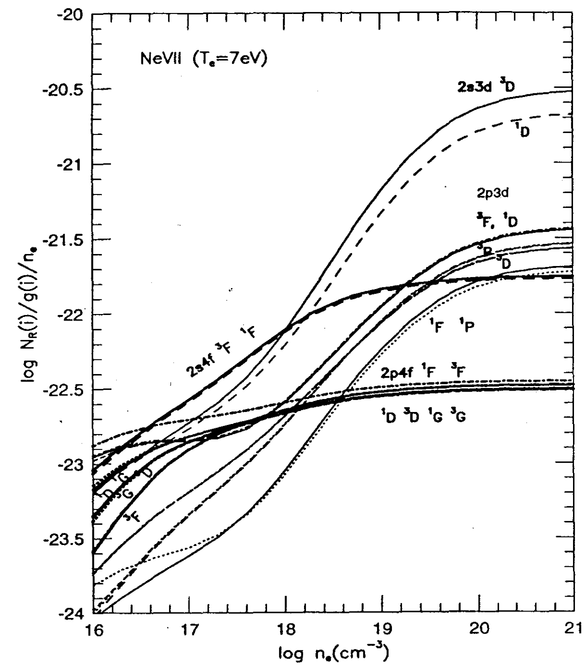

Figure 1: Normalized population densities, $n(i)/(g(i)n_e n_+)$, of 2s3d, 2p3d, 2s4f, and 2p4f levels for NeVII as a function of electron density.

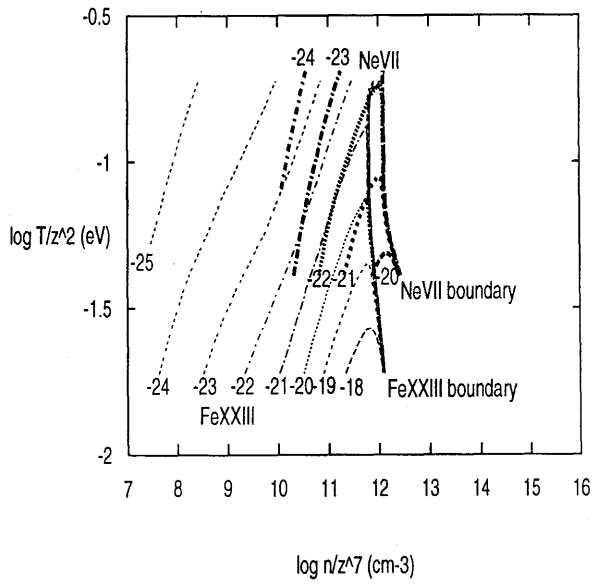

Figure 2: Contour map for the normalized gain, G', for 2s3d ^{1}D – 2s4f ^{1}F line in normalized electron density n_e/Z_{eff}^7 vs normalized electron temperature T_e/Z_{eff}^2 plane. Thin lines are for FeXXIII and thick lines for NeVII labeled with $\log G'$.